NASA's Evolution to K_a-Band Space Communications for Near-Earth Spacecraft

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Over the next several years, NASA plans to launch multiple earth-science missions which will send data from low-Earth orbits to ground stations at 1-3 Gbps, to achieve data throughputs of 5-40 terabits per day. These transmission rates exceed the capabilities of S-band and X-band frequency allocations used for science probe downlinks in the past. Accordingly, NASA is exploring enhancements to its space communication capabilities to provide the Agency's first K_a-band architecture solution for next generation missions in the near-earth regime. This paper describes the proposed K_a-band solution's drivers and concept, constraints and analyses which shaped that concept, and expansibility for future needs.

I. Introduction

For over five decades, NASA has launched and operated spacecraft for studying Earth and space phenomena. As both scientific knowledge and instrument technology have advanced during this period, the observation capabilities of these spacecraft have grown as well. The transmission rates and daily volumes of data collected by science probes orbiting the earth have correspondingly increased by several orders of magnitude. As the science data downlink rates have increased, so, too, have the signal bandwidths required to support these transmissions.

NASA, like all users of the radio spectrum, must respect frequency allocations established by the International Telecommunications Union (ITU). In ITU parlance, science data downlinks are designated as space-to-earth communications for the Earth Exploration Satellite Service or for the Space Research Service. The ITU has allocated about 5 MHz for such purposes at S-band (approximately 2-4 GHz), 10 MHz for Space Science links and 375 MHz for Earth Science links at X-band (about 7-12 GHz), and 1.5 GHz for direct downlinks and 2.25 GHz space-to-space links at K_a-band (about 19-36 GHz). With growing bandwidths needed to support increasing data rates, downlink designs have evolved over the decades from S-band to X-band, and near-term future needs compel advancing further to K_a-band.

In advance of anticipated needs for K_a-band downlinks in the near-Earth region, NASA has developed a design for its networks operating in that region to support corresponding capabilities. This approach leverages three missions, presently under development, as references for understanding relevant needs and constraints for a solution enabling K_a-band near-Earth missions of the future.

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II. Mission Requirements

A 2007 study (reference [1]) by the National Research Council recommended areas for NASA science research, observation and related spacecraft missions for following decade. This first decadal survey recommended fourteen new spacecraft missions for NASA, three for the National Oceanic and Atmospheric Administration (NOAA), and one new joint NASA/NOAA mission. These seventeen missions "form a minimal, yet robust, observational component of an Earth information system that is capable of addressing a broad range of societal needs." Three of these missions, namely HyspIRI, DESDynI, and SWOT have significant data volume requirements, as shown in Table 1, and will require K_a-band's wide spectrum allocation to accommodate signal bandwidths needed for gigabit-per-second transmission rates.

Table 1. Mission information.[1-4]

	Mission		
	DESDynI	SWOT	HyspIRI
Full Name	Deformation, Ecosystem Structure and Dynamics of Ice	Surface Water and Ocean Topography	Hyperspectral Infrared Imager
Phenomena for Study	• Earth surface deformations which may portend geologic hazards • Responses of carbon-storing terrestrial biomass, to changing climate and land management • Variations in ice flow patterns and velocities as dynamic responses to climate change	• Water levels and circulation within and between natural bodies of water • Interactions between terrestrial surface waters and coastal oceans	• Land surface composition for agriculture and mineral characterization • Vegetation types for ecosystem health
Instrument(s)	• L-band InSAR • Laser altimeter	• Ka- or Ku-band radar • Ku-band altimeter • Microwave radiometer	• Hyperspectral spectrometer
Data Volume (approx.)	40 terabits per day	7.2 terabits per day	3.5 terabits per day
Orbital Parameters	Altitude: 760 km Inclination: 98°	Altitude: 970 km Inclination: 78°	Altitude: 626 km Inclination: 98°
Contact Requirements (at 1 Gbps)	45 minutes per orbit 667 minutes per day	120 minutes per day	60 minutes per day

Whereas this study assumed these three missions would not be launched before 2015, later information suggests delays until 2019. However, President Obama's recently announced fiscal year 2011 budget requests a funding increase for Earth science missions, with the potential for accelerating these missions' schedules.

HyspIRI, DESDynI, and SWOT are representative first examples of future low-Earth orbit (LEO) missions needing K_a-band downlinks, and served as references for developing the near-Earth K_a-band capability. Migrating to K_a-band for near-Earth missions has been long expected within NASA, and is an integral part of NASA networks' planned evolution to enable high rate missions.

III. Potential Solutions

As a starting point for developing near-Earth K_a-band capabilities, NASA considered its Space Communications and Navigation (SCaN) Program's existing networks, as well as a NOAA network under development.

NASA's Near Earth Network (NEN) provides space communication ground station services for science and exploration spacecraft primarily at LEO altitudes. The NEN utilizes both NASA5 and commercial6 stations throughout the world, and provides communications as well as tracking services to spaceflight missions. One of the NEN's assets, the 18.3m "WS1" antenna at White Sands, New Mexico, provides K_a-band communication for the Lunar Reconnaissance Orbiter (LRO) mission.

NASA's Space Network (SN) comprises a set of geosynchronous Tracking and Data Relay Satellites (TDRSs) and associated ground stations at White Sands and on the island of Guam. The SN, by means of the TDRS system (TDRSS), provides services to a broad user base from near-continuous, high-data-rate users to an opportunistic community of near-immediate, unscheduled, low-data-rate missions. The SN provides communications critical for human spaceflight, such as Space Shuttle missions and the International Space Station, and supports many low-Earth orbiting spacecraft as well. TDRS satellites 8, 9, and 10 support K_a-band communication, as will the TDRS-K and -L satellites under construction.

The NASA Deep Space Network (DSN) provides communications and tracking services for space vehicles at distances well beyond the near-Earth region. As the DSN's assets and operations are optimized for the challenge of providing services over distances orders of magnitude greater than those addressed by the NEN and SN, DSN modifications for near-Earth K_a-band services were not contemplated.

NOAA's National Polar-orbiting Operational Environmental Satellite System (NPOESS) SafetyNet network of 15 ground stations located around the world was considered as an initial K_a-band solution for LEO missions, but was ultimately ruled out for multiple reasons. SafetyNet's 4m antennas would provide a link budget figure of merit (G/T) about 10 dB less than available with the baseline system, proposed below, employing 12m antennas. Spacecraft transmitters and/or antennas would have to transmit correspondingly more power to the Earth, available at the cost of increased spacecraft power and/or launch mass requirements. Also, SafetyNet is engineered for 150 Mbps downlinks, and its receivers would have to be upgraded to support 1 Gbps. Further, SafetyNet plans to install 45 Mbps circuits for backhauling data to mission operations centers. Without upgrades to this backhaul infrastructure, NASA missions would have to share the limited bandwidth, and as a second-tier customer, implying substantial delay for conveying data originally downlinked at 1 Gbps. Further, SafetyNet stations must serve NOAA's NPOESS spacecraft, and so NASA missions would have a lower priority for using these stations.

These general considerations about SafetyNet imply particular concerns for the three initial K_a-band missions described above. The 10 dB link budget figure-of-merit reduction would require redesigning SWOT's antenna system. SafetyNet scheduling constraints would allow only an average of only 540 minutes per day for DESDynI contacts, far short of the 667 minutes required. Lastly, DESDynI, SWOT and HyspIRI would all require enhancements to SafetyNet's backhaul connectivity and receivers. Since a SafetyNet-based approach implies mission-specific concerns, cannot meet initial mission requirements without significant enhancements to SafetyNet ground stations and associated backhaul infrastructures, and has no margin for future growth, SafetyNet was not pursued as a component for a new NASA K_a-band capability. However, it is apparent that individual NASA missions could be designed to meet SafetyNet's requirements.

Concerns described above leave the NEN and SN available for consideration. Ultimately, a solution employing both the NEN and SN was adopted, as will be described in subsequent sections.

IV. Coverage and Loading Analyses

Having ruled out other networks, the next step towards developing a solution was to ascertain if the NEN and/or SN could provide enough service each day for DESDynI, HyspIRI, and SWOT, given the expected orbital parameters for these spacecraft. Coverage and loading were considered before other technical considerations since the former two are constrained by mission designs and established infrastructures (such as SN spacecraft and NEN station locations) which would be leveraged without modification, whereas some freedom is available in technical designs for science mission spacecraft and new NEN antennas.

DESDynI presents the most challenging communications load among the three initial missions considered. Coverage analyses indicated a ground-based solution would require at least fifteen assets—an unreasonably large number—distributed around the world to meet the daily contact requirement of 667 minutes per day with 1 Gbps downlinks. Further studies indicated that if a 3 Gbps downlink were hypothetically available, then five NEN sites and 222 minutes of contact per day would be needed to support DESDynI's downlink volume of 40 terabits (Tb) per

day. However, space-qualified K_a-band technology was deemed insufficiently mature to allow assuming a 3 Gbps downlink would be available in time to suit DESDynI's schedule for development and launch. Accordingly, a NEN-based solution was ruled out as the prime network for receiving DESDynI's downlink data.

Loading analyses indicate an SN-based solution employing multiple TDRSS nodes each day will support DESDynI's daily data downlinking requirements. As show in Table 2 below, a solution using two TDRSS satellites (nominally TDRS-East [TDE] and TDRS-West [TDW], and assuming a medium priority for DESDynI relative to other missions served by the SN), or one employing a single TDRSS satellite (assuming DESDynI's priority is greater than those for the Hubble Space Telescope and the Terra mission) would provide more than the required 667 minutes per day of coverage. However, a single-node TDRSS solution would imply extremely heavy loading on that one satellite to support the DESDynI mission. This heavy loading motivates the recommended two-node solution for DESDynI.

While an SN-based solution was deemed most appropriate for DESDynI, a NEN-compatible communications system could be included aboard DESDynI for back-up purposes. With this additional capability, DESDynI could downlink primarily through the SN, but employ the NEN to reduce the coverage provided by the SN, as needed. Also, a dual SN-NEN communications payload aboard DESDynI could potentially use both the SN and the NEN routinely, and thereby reduce the burden on the TDRS system.

The foregoing analyses prescribe an SN-based solution for DESDynI. For SWOT and HyspIRI, which have less-challenging requirements, an SN-based solution would likely meet requirements for both missions. However, a feasible ground-based solution was conceived, which would avoid burdening the SN's satellites with loads that could be otherwise accommodated. Additionally, an SN-based solution for SWOT and HyspIRI would impose greater mass and power requirements on these spacecraft for more powerful communication payloads required to reach TDRSS satellites, which are more than an order of magnitude farther than earth stations. For these reasons, a NEN-based solution for these missions is recommended. NEN coverage and loading analysis results for SWOT and HyspIRI are summarized in Table 3.

Table 2. SN coverage and loading analysis summary for DESDynI. *A nominal spacecraft antenna configuration was assumed for these approximate results.*

SN Support Scenario	DESDynI Priority	Contact time (average minutes/day)
2 nodes (TDE, TDW)	< HST, Terra	668
1 node (TDE)	> HST, Terra	691
1 node (TDE)	< HST, Terra	640
Mission Requirement		667

Table 3. NEN coverage and loading analysis summary for SWOT and HyspIRI. *The coverage calculations have been adjusted for overlap. Alaska and Svalbard together suffice for both missions' requirements, assuming optimized scheduling. Figures for McMurdo assume SWOT and HyspIRI receive highest priority.*

	Contact time per mission (average minutes/day)	
	SWOT	HyspIRI
Alaska	51.9	21.2
Svalbard	55.1	27.5
Wallops	6.9	13.3
White Sands	16.6	7.9
McMurdo	66.6	55.7
Total	197.1	125.6
Mission requirements	120	60

V. Proposed K_a-Band Solution

The analyses summarized in the previous section suggest an SN-based solution for DESDynI and a NEN-based solution for SWOT and HyspIRI. This combined SN/NEN approach was proposed as SCaN's initial K_a-band solution, with details presented below.

A. Proposed Space and Ground Assets

The proposed station locations for the initial K_a-band capability are shown in Figure 1. The NEN currently has ground stations at each location and the proposed solution would be a mix of existing and planned antenna systems. Several attributes drove location recommendations, including existing infrastructure, coverage, rain attenuation, operational efficiencies with existing ground stations, and access to high rate fiber connections for communication with mission and science operations centers. The SN ground segment is located at the White Sands Complex, and the space segment of the envisioned initial K_a-band capability would consist of one TDRS in the east and one in the west (referenced to the White Sands location).

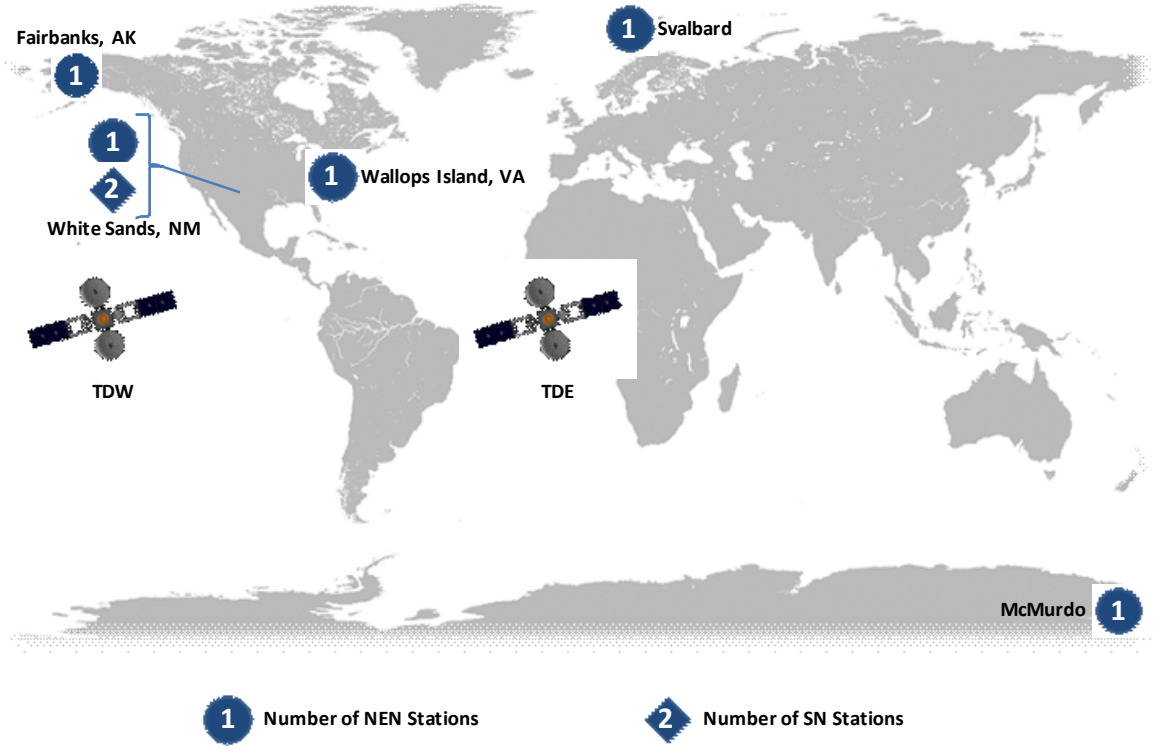


Figure 1. Proposed K_a-band ground station locations.

The NEN potion of the solution baselines construction of three new 12m-class assets (one each at Svalbard, Norway; Alaska Satellite Facility[ASF] in Fairbanks; and Wallops Island, Virginia), plus use of the White Sands 1 (WS1) 18.3m antenna and the planned second McMurdo 5.4m antenna (MG2) at the McMurdo Ground Station. The selection of a 12m-class antenna enables required link margins at low elevations and reduces procurement costs, as three-axis antennas in this class suitable for tracking polar-orbiting spacecraft are commercially available. The WS1 antenna currently supports both S- and K_a-band links for the Lunar Reconnaissance Orbiter (LRO) mission; its ground station electronics will require an upgrade to meet K_a-band decadal survey missions' data rate requirements. The MG2 antenna system will be S/K_a-band capable, but only low-rate ground station equipment is planned and budgeted at present. Deployment of the NEN K_a-band sub-network would be targeted for completion at least one year prior to the launch of the first user spacecraft.

Although an asset at each of Svalbard and Alaska can together satisfy SWOT and HyspIRI requirements, Wallops, WS1, and MG2 add site diversity to mitigate weather impacts, station/line outages, or other service disruptions. This ensemble of five NEN assets will provide an economical yet robust approach to serving K_a-band decadal survey missions.

The initial SN portion of the K_a-band network would rely on two of the five K_a-capable TDRS satellites (TDRS-8, -9, and -10 currently on orbit and the TDRS-K and -L spacecraft currently under construction) with a downlink to the White Sands Complex. As noted earlier, analysis (Table 2) indicates a single K_a-band capable TDRS could meet DESDynI mission requirements, although a two node solution would provide a better approach towards TDRS loading/scheduling and redundancy considerations.

B. Spectrum Plan and Interference Considerations

A proposed spectrum plan for the three missions identified above, respecting other users at nearby frequencies, is shown in Figure 2. This spectrum plan provides NASA missions with adequate protection from interference with NOAA's NPOESS primarily by using the opposite polarization from the NPOESS missions.

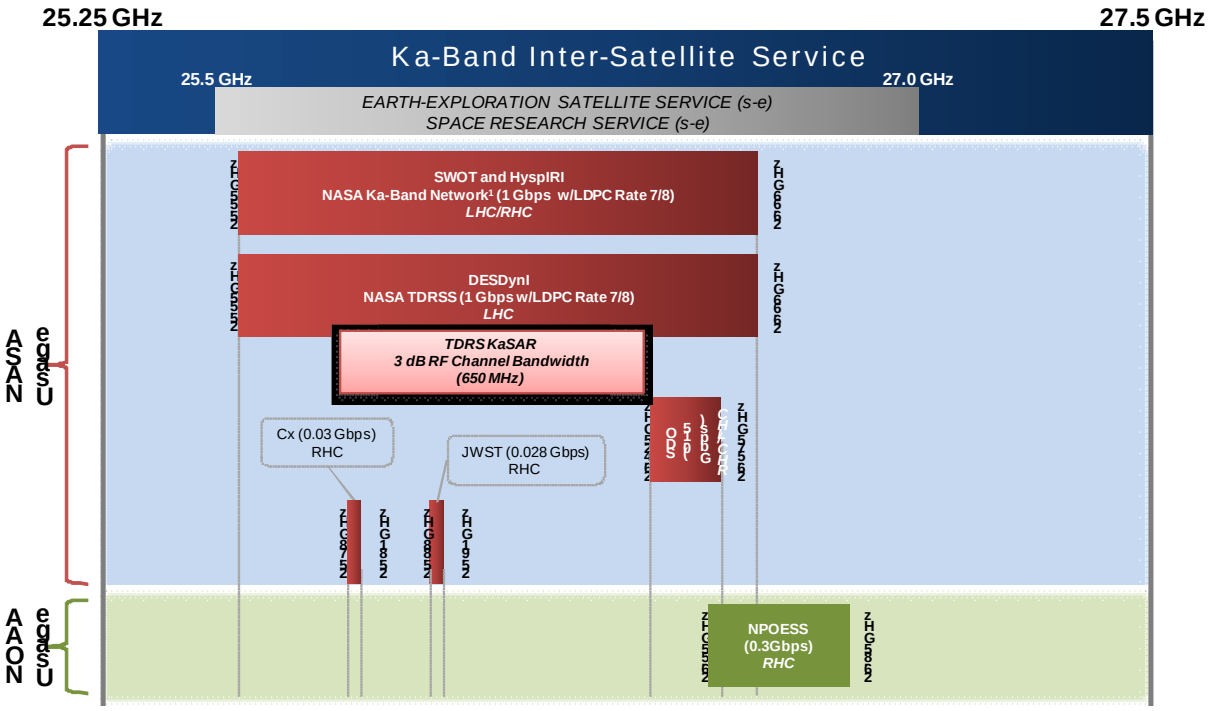


Figure 2. Proposed K_a-band spectrum plan.

In addition to spectrum considerations, possible interferences between the decadal survey missions and other missions were analyzed as well. Studies of orbital coincidences between the NPOESS satellites and the SWOT and HyspIRI missions indicate these coincidences are sufficiently rare that the narrow beam of the new K_a 12m antennas will essentially preclude any significant interference. Potential interference to or from other NASA K_a-band missions, such as the Solar Dynamics Observatory (SDO), the James Webb Space Telescope (JWST), and Constellation program vehicles, can be accommodated through careful scheduling. The new antennas at the high-latitude ground station sites of Svalbard and Alaska will have narrow beamwidths and so will provide geometric isolation between the multiple spacecraft which use those sites. The mid-latitude sites at White Sands and Wallops will need to be carefully scheduled to provide required isolation. SDO, at geostationary Earth orbit (GEO) altitude, uses dual 18m antennas at White Sands on a 24x7 basis, so White Sands contacts with polar-orbiting spacecraft should not be scheduled when these LEO spacecraft transit through SDO's antenna beams. It should be noted that SDO uses both polarizations, so isolation between SDO and polar-orbiting missions cannot be achieved by using orthogonal polarizations. Fortunately the requirements for the decadal survey missions can be satisfied primarily with the high-latitude sites, so limiting contacts with mid-latitude sites should not present a problem.

Additionally, JWST is a libration point mission that will use a DSN 34m antenna at Goldstone, California for a few hours per day. From Goldstone, the view to JWST will be towards the east, so passes at White Sands and Wallops for polar-orbiting spacecraft will again have to be scheduled carefully. Fortunately, another mitigating factor in this case is that the JWST signal levels will be significantly lower than the LEO spacecraft signals supporting 1 Gbps, so interference from JWST is not expected to be significant. The ground network for Constellation has not yet been designed, but again judicious scheduling with the mid-latitude sites should suffice to minimize potential interference.

C. Link Analysis Summary

Due to the very large daily data volume required by DESDynI, a ground station solution would have required at least fifteen ground stations scattered across the globe, all designed to receive the 1 Gbps downlinks. Considering not only the initial investment but the maintenance and operation costs, as well as the cost to retrieve the data back to CONUS, an SN-based solution was selected. The second- and third-generation TDRS payloads have K_a capability and the supporting ground terminals will be engineered to process 1 Gbps. To meet DESDynI's daily volume of 40 terabits per day, 45 minutes per orbit of TDRS time will be required. In the time frame following launch of the three missions considered for this study, it is expected there will a compatible TDRS node in the east (nominally 41^0 west longitude) and one in the west (nominally 174^0W). Loading studies indicate this 45 minute requirement can be satisfied. Should only a single TDRS be available, priorities of other users would have to be adjusted to maintain DESDynI support. DESDynI has sufficient mass/power to support radio frequency (RF) components for closing the link to TDRS. As a backup, a second antenna for potential operation to ground terminals is also planned. Once DESDynI data arrives at the TDRS ground terminal in White Sands, it will be sent to the mission operations center at the Jet Propulsion Laboratory in Pasadena, California via NASA Integrated Services Network (NISN) infrastructure. In addition to the K_a 1Gbps link, S-band telemetry, telecommand and control (TT&C) links through TDRS will also be provided. For the DESDynI link through TDRS, there is a limiting filter (650 MHz bandwidth) aboard TDRS that will constrain the achievable throughput. Test results indicate a 1 Gbps data rate using LDPC-7/8 encoding and QPSK modulation is a practical upper limit. Ground-based receivers/decoders supporting this rate are now commercially available.

For SWOT and HyspIRI, the spacecraft antenna size must be constrained to limit jitter induced to the spacecraft from antenna movement. With this constraint, link closure to TDRS was deemed infeasible, and a ground terminal solution was developed.

Considering both geometry and atmospherics effects on K_a band, studies were done to define a set of ground terminals to meet SWOT's and HyspIRI's daily downlink volumes of 7.2 and 3.5 terabits per day, respectively. Since each of these missions have highly-inclined orbits, high-latitude ground terminals will provide the most geometric coverage, and also yield lower atmospheric attenuation at K_a band than would mid-latitude terminals. Using the ITU global model, the atmospheric effects were computed for each proposed site. Since the atmospheric effects depend on location, Alaska was arbitrarily chosen as the baseline site in developing a link design, targeting a 3 dB link margin at 10^0 elevation and an availability of 99%. Because of this selection, and the two missions having slightly different orbits, the analysis yielded different link margins for the other sites and for each mission, assuming a fixed 1 Gbps downlink. The 1 Gbps rate was assumed because it was reasonably believed a space-qualified modulator/encoder/transmitter would be available in time for these missions. The ground antenna size was initially set at 12m based on an assumed requirement for the antenna to have full motion ability for accurately tracking LEO polar orbits at K_a band. Later inputs from manufacturers indicate that 13m antennas can perform equally as well and are readily available, so it is expected such larger antennas will be procured. The existing 18m WS1 antenna at White Sands has K_a band capability and so it will be part of the support network for a small number of passes per day.

Table 4 summarizes link margins for the K_a-band 1 Gbps link for the TDRS (SN) and direct-to-ground (NEN) solutions. Note the final link margins are site-dependent; in the case of Wallops, the availability target was reduced slightly, and the elevation angle increased, to obtain the required 3 dB link margin.

The conclusion from these analyses is that a combination of the SN and proposed NEN K_a network can meet the requirements of the three missions studied with viable RF link designs.

Table 4. Link analysis summary.

Mission	SN	NEN Stations: Alaska (12m)	Svalbard (12m)	Wallops (12m)	WS1 (18.3m)	McMurdo (5.4m)
DESDynI *(1 Gbps, OQPSK, Rate-7/8 LDPC)* EIRP to SN = **60.3 dBW**	M = 2 dB AA = 99%	N/A	N/A	N/A	N/A	N/A
SWOT *(1 Gbps, OQPSK, Rate-7/8 LDPC)* EIRP to NEN = **28.8 dBW**	N/A	M = 3 dB AA = 99% (EA = 10^0)	M = 4.7 dB AA = 99% (EA = 10^0)	M = 3 dB AA = 95% (EA = 12.1^0)	M = 4.9 dB AA = 99% (EA = 10^0)	M = 3 dB AA = 99% (EA = 17.5^0)
HyspIRI *(1 Gbps, OQPSK, Rate-7/8 LDPC)* EIRP to NEN = **26.2 dBW**	N/A	M = 3 dB AA = 99% (EA = 10^0)	M = 4.7 dB AA = 99% (EA = 10^0)	M = 3 dB AA = 95.3% (EA = 12^0)	M = 4.9 dB AA = 99% (EA = 10^0)	M = 3 dB AA = 99% (EA = 16^0)

M = Margin; AA = Annual Availability; EA = Elevation Angle; N/A = not applicable

D. Frequency Reuse and Propagation Impairments

In anticipation that future missions may require data rates exceeding the 1 Gbps figure considered for the initial implementation, the NEN ground terminal design will allow for frequency reuse using orthogonal polarizations. Note that almost all of the available 1.5 GHz in the current spectrum plan would be consumed with a 1 Gbps QPSK signal with LDPC-7/8 encoding. Dual-polarization frequency reuse effectively allows for a doubling of the downlink data rate without consuming any additional spectrum. In the proposed NEN ground station antenna system configuration, the terminals will have the capability to process both polarizations from the spacecraft downlinks. The impact to the spacecraft for using both polarizations will be requirements for dual transmitter chains and the ability to radiate both left- and right-hand polarizations, each with its own 1 Gbps data stream. Dual polarization frequency reuse in satellite systems is well documented, and is currently being used at 20 GHz for dual 819 Mbps frequency reuse channels (i.e. achieving a total downlink rate of 1.64 Gbps).7

Typically, isolation between the two channels should exceed 20 dB, and performance depends highly upon the axial ratio of both the transmitting and receiving antennas, preferably as close to 1 dB as possible. Because high-latitude sites will be utilized, there was a concern that precipitation (snow, ice, freezing rain)-related propagation impairments would reduce the isolation. To this end, a literature search was conducted and additional analysis specific to 26 GHz was performed; some of the pertinent sources are cited in the references, and a summary of the 26 GHz propagation analysis is given below.

Propagation impairments that affect K_a-band links include rain attenuation, cloud attenuation, gaseous absorption, and scintillation fading. Table 5 shows the magnitudes of the different impairments predicted using ITU-R Recommendation P.618-9 for the five K_a-band station sites envisioned: ASF, Svalbard, White Sands, Wallops Island, and McMurdo. The table also shows the cross-polar discrimination (XPD) induced by the atmosphere, which is a measure of the polarization isolation. In the case of rain, XPD or isolation decreases with increasing rain attenuation. For links that cannot tolerate large rain fades, the impact of rain depolarization is not considered significant. Table 5 indicates that rain fade levels less than about 3 dB correspond to XPD levels exceeding 25 dB. As an example, the link degradation produced by an XPD of 25 dB on a link operating at a typical carrier-to-noise power ratio (C/N) level of 12 dB is approximately 0.2 dB. On the other hand, ice depolarization normally occurs without significant signal fading, and can reach levels below those expected from rain alone. However, a small rain fade margin built into the link may be sufficient to compensate for degradations produced by ice depolarization as well.

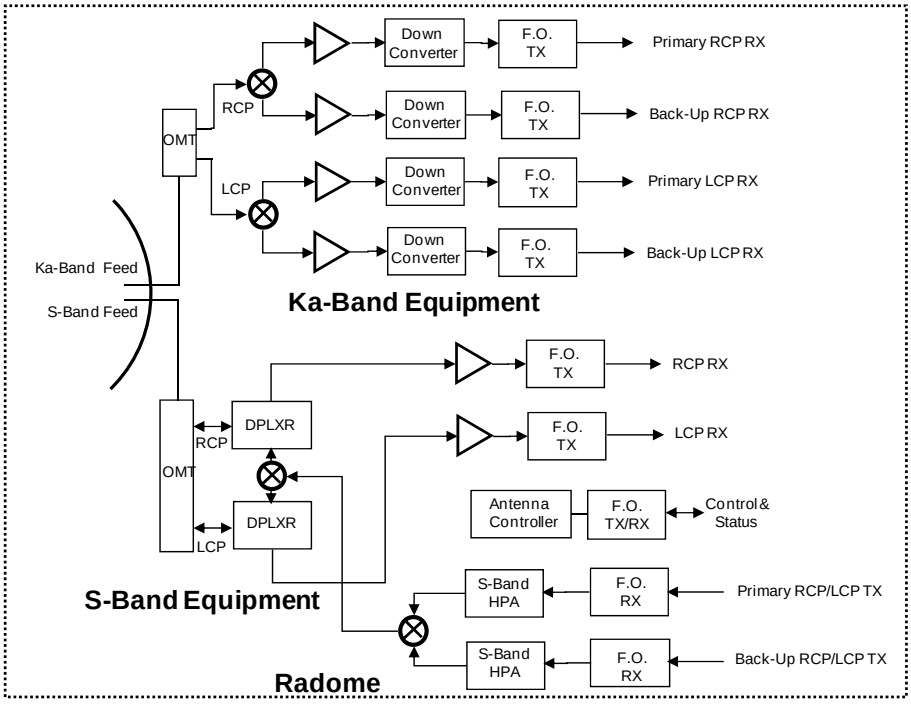
Table 5. Propagation impairments at proposed future Ka-band station sites.

Ground Station Information		Propagation Impairments for Percent Availability														
		95%					97%					99%				
Name, Latitude, Longitude, Height above MSL	Elevation Angle (°)	Rain Atten. (dB)	Gas Abs. (dB)	Scint. Fade (dB)	Total Fade (dB)	XPD (dB)	Rain Atten. (dB)	Gas Abs. (dB)	Scint. Fade (dB)	Total Fade (dB)	XPD (dB)	Rain Atten. (dB)	Gas Abs. (dB)	Scint. Fade (dB)	Total Fade (dB)	XPD (dB)
Fairbanks, AK	5	1.32	1.82	0.83	3.38	32.51	1.92	1.82	1.00	3.99	29.92	4.06	1.82	1.36	6.10	24.56
65.974° N	10	0.77	0.95	0.29	1.77	36.97	1.14	0.95	0.35	2.13	34.36	2.44	0.95	0.48	3.44	28.96
147.512° W	15	0.57	0.64	0.15	1.23	39.70	0.84	0.64	0.18	1.50	37.09	1.83	0.64	0.25	2.48	31.67
549.0 m	20	0.46	0.48	0.10	0.96	41.77	0.68	0.48	0.12	1.18	39.15	1.50	0.48	0.16	1.99	33.72
Svalbard, Norway	5	0.71	1.87	0.83	2.96	37.54	1.04	1.87	1.00	3.31	34.93	2.24	1.87	1.37	4.49	29.51
78.23072° N	10	0.40	0.97	0.29	1.46	42.27	0.59	0.97	0.35	1.66	39.64	1.31	0.97	0.48	2.36	34.18
15.3896° E	15	0.29	0.65	0.15	0.98	45.17	0.43	0.65	0.19	1.12	42.53	0.96	0.65	0.25	1.65	37.05
466.3 m	20	0.23	0.50	0.10	0.75	47.35	0.34	0.50	0.12	0.86	44.71	0.78	0.50	0.16	1.29	39.22
White Sands, NM	5	3.18	2.08	0.83	5.37	25.49	4.56	2.08	1.00	6.74	22.93	9.28	2.08	1.37	11.46	17.66
32.5425° N	10	1.88	1.07	0.26	2.97	29.86	2.72	1.07	0.32	3.81	27.29	5.65	1.07	0.44	6.74	21.97
106.6121° W	15	1.40	0.72	0.13	2.13	32.49	2.03	0.72	0.16	2.76	29.91	4.28	0.72	0.22	5.01	24.58
1485 m	20	1.15	0.55	0.08	1.7	34.45	1.68	0.55	0.1	2.23	31.86	3.56	0.55	0.13	4.11	26.52
Wallops Island,	5	4.12	4.02	1.45	8.40	23.42	5.87	4.02	1.75	10.15	20.87	11.85	4.02	2.39	16.11	15.62
VA 37.9235° N	10	2.54	2.07	0.51	4.66	27.46	3.65	2.07	0.62	5.77	24.90	7.49	2.07	0.85	9.61	19.61
75.4761° W	15	1.93	1.40	0.27	3.34	29.93	2.78	1.40	0.33	4.20	27.37	5.78	1.40	0.44	7.20	22.06
4.3 m	20	1.60	1.06	0.17	2.67	31.80	2.32	1.06	0.20	3.39	29.23	4.86	1.06	0.28	5.92	23.92
McMurdo, Antartica	5	0.02	1.28	0.78	2.06	65.16	0.03	1.28	0.94	2.22	62.42	0.09	1.28	1.29	2.57	56.69
77.83913° S	10	0.01	0.67	0.31	0.98	71.73	0.02	0.67	0.38	1.05	68.96	0.04	0.67	0.52	1.19	63.16
193.333° E 206.4	15	0.01	0.45	0.18	0.64	75.56	0.01	0.45	0.22	0.67	72.79	0.03	0.45	0.30	0.76	66.95
m	20	0.00	0.34	0.12	0.47	78.35	0.01	0.34	0.15	0.49	75.57	0.02	0.34	0.20	0.55	69.72

The conclusions developed from the literature survey and the propagation analysis are: (a) careful attention must be paid to the axial ratios of both the transmitting and receiving antennas; (b) snow accumulation on radomes should be reasonably managed but is not a major source of isolation reduction; and (c) ice particles and freezing rain can reduce polarization isolation. However, the amount of rain at the candidate high-latitude sites is relatively small, and a small fade margin will compensate for both rain fades and ice depolarization.

E. NEN Ground Station Antenna Systems

The basic functions of new (or enhanced) NEN antenna systems required for the K_a-band capability are described in a request for information (RFI)8 NASA issued in July 2009. The proposed antenna system configuration is shown in Figure 3. Key assumptions for this system, developed by link calculations, appear in the figure as well. The S-band capability is included to allow for a two-way telecommand/spacecraft bus telemetry link through the same antenna as supporting the K_a-band downlink. RFI responses received indicate low programmatic risk for achieving this configuration.



Key Features

- Aperture size >= 12m
- Continuously track LEO satellites at >= 500 km altitude.
- Ka-band receive: simultaneous LHCP and RHCP, G/T 42.7 dB/°K.
- S-band receive: simultaneous LHCP and RHCP, G/T 23 dB/°K
- S-band transmit: 63 dBW EIRP

LHCP = Left-hand circular polarization; RHCP = right-hand circular polarization

Figure 3. Proposed NEN ground station antenna system configuration.

F. Wide Area Network

The Decadal Survey Mission's Wide Area Network (WAN) requirements will be met through the NASA Integrated Services Network (NISN) infrastructure to ensure the required connectivity will exist to meet the individual missions' latency requirements. Bandwidth calculations show a minimum required bandwidth for the three reference missions of 490.1 Mbps would be necessary to transfer the expected daily volume in a 24-hour period. A recommended bandwidth of 735.1 Mbps assumes a 50% contingency to account for instances when data transfer would be slowed or lost due to NISN outages equipment malfunctions, retransmissions, or unforeseen issues. With the exception of the NEN site at McMurdo, all ground stations are placed on WAN nodes and allow low-cost service by expanding on current NASA WAN requirements.

Given the vast amounts of data down linked to McMurdo at 1Gbps, no commercial WAN service is feasible. Therefore NASA proposes to refurbish the McMurdo TDRS Relay System-2 (MTRS-2). This system comprises is a 300 Mbps-capable ground station for uplinking to TDRS and then downlinking to the White Sands Complex. For McMurdo to effectively support the higher data rates of K_a-band missions, MTRS-2 would have to be upgraded to a K_a-band uplink to TDRS.

VI. Technology Considerations

Multiple technologies will be needed to support the initial K_a-band missions' communication needs. The key considerations affecting hardware selection are forecasted availability at a prescribed technological maturity and the 1 Gbps minimum data rate needed to transport the enormous daily data volumes. At the spacecraft end of the K_a-band link, data storage technologies are needed to buffer data for transmission between contacts with earth stations. Multi-terabit space-qualified storage systems exist today and so do not pose a technological risk. Channel coding hardware, for protecting data during transmission, has been demonstrated at rates exceeding 600 megasymbols per second (Msps), which can be applied in a pair for achieving 1.2 Gbps through two orthogonal channels. A space-qualified K_a-band modulator for 1 Gbps is forecasted to exist in time to support the three initial K_a-band missions considered, based on expected industry developments and possible NASA-funded development efforts. K_a-band travelling wave tube amplifiers (TWTAs) and physical link components, for amplifying the modulated signal to the

necessary transmission power and conveying it through and beyond the spacecraft, have established flight heritage and can be applied for these missions as well.

At the terrestrial end of the link, all ground station elements are commercially available and require no further development. The SN's existing antennas for TDRS communication will support DESDynI without modification. For the envisioned NEN ground stations, candidate 12-14m K_a-band antenna systems and corresponding radomes from commercial providers have been identified. Gigabit-per-second receivers are commercially available as well; there are plans to procure such equipment as part of SN upgrades already conceived, and NEN plans are in formulation.

This analysis indicates all components needed for the K_a-band capability either exist today or are expected to exist in time to support the initial decadal survey K_a-band missions.

VII. Further Considerations

Recent experience with the DSN and the new 18m WS1 aperture supporting LRO indicate that having the ability to recover data that might be lost in K_a-band downlinks due to weather is a prudent design strategy. Protocols that conduct selective retransmission, such as the CCSDS File Delivery Protocol (CFDP) incorporated by LRO, have proven an efficient method for complete data delivery. Use of CCSDS Space Link Extension (SLE) standards will enable international interoperability at the link layer, while the potential support for Internet Protocol (IP) and Delay/Disruption Tolerant Networking (DTN) will provide a means for standardized network layer cross support.

With a baseline NASA K_a-band near-Earth capability, SN and NEN assets could be augmented as needed for new missions when required. NASA will have two new K_a-band capable TDRS spacecraft (TDRS-K/L) launched in 2012 and 2013, and has contract options for an additional two spacecraft. Given a baseline NEN K_a-band sub-network which can support approximately ten polar K_a-band missions, new antenna systems could be provided by NASA, partners, or commercial service providers. It is expected foreign space agencies will also adopt K_a-band for extremely high data rate missions in the future, and partnerships are likely to arise as they exist today in many joint missions. Partnership arrangements with foreign space agencies could be reimbursable agreements, or formulated as *quid pro quo* to enable science data sharing.

While the antenna block diagram (Figure 3) shows dual polarization, this feature could be designed but not populated with ground station equipment as a possible cost reduction. If so, the ground station equipment could be upgraded at a later date as mission requirements exceed 1 Gbps, doubling the ground station capability without any technology advancements. With inevitable technology advancements in the space and ground systems, space-ground downlink capabilities will eventually improve, perhaps to as much as 3 Gbps. Such higher data rates could allow fewer contacts per day or shorter passes for the NEN—assuming the science requirements do not keep pace. Improving the SN link performance for higher than 1.2Gbps would require a newer generation of TDRS spacecraft.

Finally, while the approach presented here applies available technologies to identified reference mission needs, NASA will continue analyzing technologies and needs as they evolve, to effectively and efficiently support Earth- and space-science mission communications.

VIII. Conclusion

Earth- and space-science missions in the foreseeable future will require K_a-band communications to support their extremely high data rates. Such communications are feasible today in the SN, and can be implemented for the NEN using COTS technology in advance of mission launch dates. The proposed K_a-band architecture described builds on existing assets where possible, reducing the cost of the overall solution. Continued cooperation between NASA's Science Mission Directorate and SCaN will ensure K_a-band communications capabilities will exist to support upcoming spacecraft missions.

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